(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 0 838 866 A2

(12) EUROPEAN PATENT APPLICATION

(43) Date of publication:
29.04.1998 Bulletin 1998/18

(51) Int Cl.[6]: H01L 33/00

(21) Application number: 97308570.7

(22) Date of filing: 28.10.1997

(84) Designated Contracting States:
AT BE CH DE DK ES FI FR GB GR IE IT LI LU MC NL PT SE

(30) Priority: 28.10.1996 US 736843

(71) Applicant: GENERAL ELECTRIC COMPANY
Schenectady, NY 12345 (US)

(72) Inventors:
- Doughty, Douglas Allen
  Charlton, New York 12019 (US)
- Liu, Yung Sheng
  Schenectady, New York 12309 (US)
- Duggal, Anil Raj
  Niskayuna, New York 12309 (US)

(74) Representative: Goode, Ian Roy et al
London Patent Operation
General Electric International, Inc.,
Essex House,
12-13 Essex Street
London WC2R 3AA (GB)

(54) A light-emitting diode white light source

(57) A system of at least three multi-coloured LED's has an optimized colour rendering index by proper selection of wavelengths of each LED, such system being useful for general illumination purposes. In a preferred embodiment, a blue LED has a wavelength in the range 455 to 490 nm, a green LED has a wavelength in the range 530 to 570 nm, and a red LED has a wavelength in the range 605 to 630 nm.

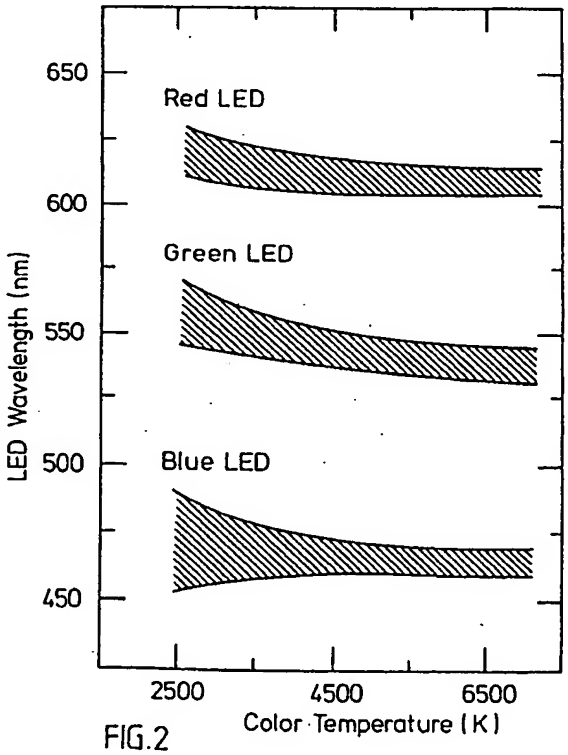

FIG.2

EP 0 838 866 A2

BEST AVAILABLE COPY

Printed by Jouve, 75001 PARIS (FR)

Description

The present invention relates generally to light-emitting diodes and, more particularly, to using light-emitting diodes as a white light source for general illumination purposes.

Significant advances have been made in the technology of light-emitting diodes (LED's) since their invention in the 1960's. In the 1980's, red-emitting AlGaAs LED's were developed with external quantum efficiencies greater than 10%, such devices actually being more energy efficient and longer lasting producers of red light than red-filtered incandescent bulbs. For this reason, they are now cost-effective replacements for standard incandescent light sources in various applications such as automotive brake lights. More recently, high-efficiency light-emitting diodes have been developed and are commercially available in the blue and blue-green wavelength range based on the InGaN and AlGaN material systems. External quantum efficiencies of 5.4% in the blue and 2.1% in the blue-green have been demonstrated with these materials. This same material system has more recently been extended into the green and yellow color range with an external quantum efficiency greater than 1%. Alternative material systems based on ZnSe or II-VI compounds have been demonstrated to yield comparable efficiencies in the green to blue wavelength range.

White-light LED systems are commercially available, but they are not competitive with standard white-light sources in either performance or cost. Accordingly, it is desirable to provide an LED system that is competitive with traditional light sources for general illumination purposes.

A system of at least three multi-colored LED's has an optimized color rendering index (R_a) by proper selection of the wavelengths of each LED. In a system with at least three LED's, $R_a > 80$ can be achieved; and in a system with at least four LED's, $R_a > 85$ can be achieved. Such systems are useful for general illumination purposes.

The features and advantages of the present invention will become apparent from the following detailed description of the invention when read with the accompanying drawings in which:

FIG. 1 graphically represents relative spectral power distribution versus wavelength for each model system for the three-LED systems set forth in Table II;

FIG. 2 graphically represents how the wavelengths that maximize the color rendering index (R_a) vary as a function of blackbody temperature;

FIG. 3 graphically represents efficacy of a three-LED system as a function of quantum efficiency of the LED's; and

FIG. 4 graphically represents the spectral power distribution of a four-LED system at 6000 K.

For general illumination purposes, the critical performance parameters for a light source are its color, its efficiency in providing light detectable by the human eye, and the way in which colors illuminated by the light source look to the human eye. These three parameters are described quantitatively by the chromaticity, efficacy, and color rendition index (R_a), respectively. In accordance with the present invention, a color model for combinations of two or more LED's has been developed and used to determine values for chromaticity, efficacy, and color rendition index (R_a).

The first step in defining an LED system is to specify the desired chromaticity of the system. The chromaticity of a light source is determined by integrating the source spectrum weighted with the spectral tristimulus functions as follows:

$$X=\int S(\lambda)\bar{x}(\lambda)d\lambda,\ Y=\int S(\lambda)\bar{y}(\lambda)d\lambda,\ Z=\int S(\lambda)\bar{z}(\lambda)d\lambda, \tag{1}$$

where X, Y, and Z are the tristimulus values (i.e., the magnitudes of the three imaginary primary colors in the 1931 CIE (Commission Internationale de l'Eclairage) system, S (λ) is the source spectral power distribution (power per unit wavelength), and $\bar{x}$, $\bar{y}$, and $\bar{z}$ are the spectral tristimulus functions. The integrations are carried out over a wavelength interval from 380 to 770 nm. The chromaticity coordinates are then given by

$$x=\frac{X}{X+Y+Z},\ y=\frac{Y}{X+Y+Z} \tag{2}$$

It is usually desirable that an illumination source have a chromaticity near the locus of points in chromaticity space that correspond to blackbody sources. In this model, three systems have been considered, two corresponding to blackbody sources at 2800 K and 3500K, and a daylight source at 6000K. (The chromaticity of daylight is slightly different from that for a black body.) Table I lists the three systems with their corresponding chromaticity coordinates.

BEST AVAILABLE COPY

Table I

System	Color Temperature	(x,y) coordinates	
LED-1	2800	0.452,	0.409
LED-2	3500	0.405,	0.391
LED-3	6000	0.322,	0.338

Color mixing is an additive process, so that given $S_i(\lambda)$ for each of n LED's, the X tristimulus value of the system is given by

$$X_T = \sum_{i=1}^{n} X_i \quad , \tag{3}$$

Values for Y_T and Z_T are determined in similar manner. Let $S_i(\lambda) = A_i f_i(\lambda)$, where A_i is the amplitude of each LED and $f_i(\lambda)$ is the LED lineshape function. Using this expression and Equations (1), (2), and (3), the chromaticity coordinates for the system can be derived and are given by

$$x_T = \frac{\sum_{i=1}^{n} x_i A_i F_i / y_i}{\sum_{i=1}^{n} (X_i + Y_i + Z_i)}, \qquad y_T = \frac{\sum_{i=1}^{n} A_i F_i}{\sum_{i=1}^{n} (X_i + Y_i + Z_i)} \quad , \tag{4}$$

where F_i is the integral of $f_i(\lambda)$ weighted with $\bar{y}$.

The amplitude of each LED can be determined by solving Equation (4) for A_i. If it is possible to attain the desired chromaticity coordinates with the given LED's, then at least one solution to equation (4) will exist. For $n \leq 3$, this solution provides a unique determination of the relative amplitudes required for the individual LED's. For $n > 3$, however, Equation (4) is underdetermined so that, in general, more than one solution for the relative amplitudes exists.

In this model, $f_i(\lambda)$ is a Gaussian function for each LED. The spectral distributions of actual LED's show that the core of the lineshape is well-approximated by a Gaussian, but the "wings" tend to be more intense than a Gaussian; in addition, there tends to be some asymmetry in the actual spectral distribution with more intensity on the longer wavelength side of the peak. Since most of the power per unit wavelength is contained in the core of the lineshape, the use of a Gaussian will provide a good approximation to an actual LED system. The spectral linewidth of the LED is not an independent parameter. In energy space the spectral width is only dependent on the device temperature, so that in wavelength space the width is proportional to the square of the peak wavelength. The linewidth used in these calculations was determined from commercial LED spectra and was found to be ~0.06 eV at 25°C.

The two critical figures of merit for an LED white-light system are the efficacy and the general color rendering index. The efficacy is the photometric analog of the radiometric efficiency; i.e., the efficiency is the ratio of the visible power produced to the input electrical power, whereas the efficacy is the ratio of the integral of the visible power per unit wavelength weighted by the photopic eye response to the input electrical power. The efficacy for an LED system can be expressed as:

$$\varepsilon = K \int \bar{y}(\lambda) \left(\sum_{i=1}^{n} \frac{S_i(\lambda) \eta_i}{\int S_i(\lambda) d\lambda} \right) d\lambda \quad , \tag{5}$$

where K = 683 lumens per visible watt and η_i is the external quantum efficiency of the ith LED, $\bar{y}$ being the normalized photopic eye response function. A typical 100 Watt incandescent lamp has an efficacy of 18 lumens/Watt while a typical

BEST AVAILABLE COPY

40 Watt "cool white" fluorescent lamp has an efficacy of 72 lumens/Watt.

The color rendering index is a quantitative measure of how different an object will appear when illuminated by a particular source as compared to a standard source. There are fourteen test objects specified by the CIE that are used in the calculation of color rendering. The specification of each test object is given by a reflectance function, i.e., the fractional reflected power per unit wavelength. Briefly, the calculation consists of determining the tristimulus values of the test objects when illuminated by the source of interest and by a standard source. Each tristimulus value is given by the integral of the source spectral power distribution weighted by the tristimulus function and the reflectance function. A color difference between two points in chromaticity space is defined, and is used to calculate the color difference between a given test object when illuminated by the source of interest and the same test object illuminated by the standard source. This yields fourteen special color rendering indices. The general color rendering index R_a is the arithmetic average of the first eight of these indices. The scale is set such that a blackbody source will have an R_a of 100 and a 3000 K "warm white" fluorescent lamp will give an R_a of 50. Since a blackbody is used as the standard source for color temperatures less than 5000 K, $R_a \equiv 100$ for an incandescent lamp.

In accordance with the present invention, systems of at least three LED's have been optimized for high color rendering capability in a manner heretofore unknown such that such three-LED systems are suitable for general illumination purposes. In a preferred embodiment, the selected wavelength for a first of the three light-emitting diodes is in a range from approximately 530 to approximately 570 nm, the selected wavelength for a second of the three light-emitting diodes is in a range from approximately 455 to approximately 490nm, and the selected wavelength for a third of the three light-emitting diodes is in a range from approximately 605 to approximately 630 nm.

Table II lists wavelengths that maximize R_a for a three-color system at three preselected chromaticity points. Advantageously, $R_a > 80$ for these systems, comparable to good color-rendering fluorescent lamps.

Table II

Color Temperature (K)	λ_1(nm)	λ_2(nm)	λ_2(nm)	R_a	Efficacy (lumens/Watt)
2800	482	559	621	86.3	35.2
3500	466	547	614	84.1	39.0
6000	463	542	610	83.0	35.8

The efficacies listed in Table II are obtained for the wavelengths that maximize R_a while assuming $\eta_i = 0.1$ for each LED, efficacy being a function of η_i. The amplitude for each LED needed to yield the chromaticities in Table I are shown in FIG. 1 which is a graph of relative spectral power distribution versus wavelength for each model system.

FIG. 2 graphically illustrates how the wavelengths that maximize R_a for a three-LED system vary as a function of blackbody temperature. LED's chosen from each of the cross-hatched regions will result in an $R_a > 80$. In general, a particular application requires a particular chromaticity. In accordance with the present invention, FIG. 2 is used to select the wavelengths of the LED's that provide the highest available color rendering for that temperature. Similar curves can be generated for chromaticities off the blackbody locus, but such sources are less desirable for general lighting applications.

FIG. 3 is a plot of how the efficacy of the 3500 K three-LED case in Table II extrapolates as the external quantum efficiencies for the LED's increase (assuming η_i is the same for all three LED's). Shown for comparison are the efficacies for some current technology lighting sources with which white-light LED systems might compete.

An enhanced color rendering system may be achieved with four LED's. In a preferred embodiment, the selected wavelength for a first of the four light-emitting diodes is in a range from approximately 440 to approximately 450 nm, the selected wavelength for a second of the four light-emitting diodes is in a range from approximately 455 to approximately 505 nm, the selected wavelength for a third of the four light-emitting diodes is in a range from approximately 555 to approximately 565 nm, and the selected wavelength for the fourth light-emitting diode is in a range from approximately 610 to approximately 620 nm.

Table III lists four wavelengths that have been determined to yield incandescent-like values of R_a.

Table III

λ_1(nm)	λ_2(nm)	λ_3(nm)	λ_4(nm)	R_a	Efficacy (lumens/Watt)
445	500	557	615	96.0	31.3

FIG. 4 graphically illustrates the relative intensity of the four-LED system specified in Table III. Not only is R_a quite high, but all except one of the special color rendering indices are in excess of 90. When compared with the results in Table II for a three-LED system, R_a is increased by 16% and the efficacy is decreased by 13%. (Efficacy will generally

BEST AVAILABLE COPY

decrease when R_a increases since the spectral power is distributed over a broader wavelength range.) Because of the significantly increased computational time associated with searching for the maximum R_a in five-dimensional space (four wavelengths and one additional amplitude), only a fraction of parameter space was considered. Thus, the results in Table III do not necessarily represent the global maximum for R_a. Advantageously, however, these results clearly demonstrate that exceptional color rendering is possible with an LED system.

Claims

1. A general illumination system, comprising:
   at least three light-emitting diodes, each light-emitting diode providing visible light at a preselected wavelength for optimizing color rendition index for the system.

2. The system of claim 1 wherein the wavelength for each light-emitting diode is preselected by maximizing color rendition index using wavelength versus color temperature data

3. The system of claim 1, comprising three light-emitting diodes, the wavelength for each light-emitting diode being selected such that the color rendition index for the system is at least approximately 80.

4. The system of claim 3 wherein the selected wavelength for a first of the three light-emitting diodes is in a range from approximately 530 to approximately 570 nm, the selected wavelength for a second of the three light-emitting diodes is in a range from approximately 455 to approximately 490 nm, and the selected wavelength for a third of the three light-emitting diodes is in a range from approximately 605 to approximately 630 nm.

5. The system of claim 1, comprising at least four light-emitting diodes, the wavelength for each light-emitting diode being selected such that the color rendition index for the system is at least approximately 85.

6. The system of claim 5 wherein the selected wavelength for a first of the light-emitting diodes is in a range from approximately 440 to approximately 450 nm, the selected wavelength for a second of the light-emitting diodes is in a range from approximately 455 to approximately 505 nm, the selected wavelength for a third of the light-emitting diodes is in a range from approximately 555 to approximately 565 nm, and the selected wavelength for a fourth of the light-emitting diodes is in a range from approximately 610 to approximately 620 nm.

BEST AVAILABLE COPY

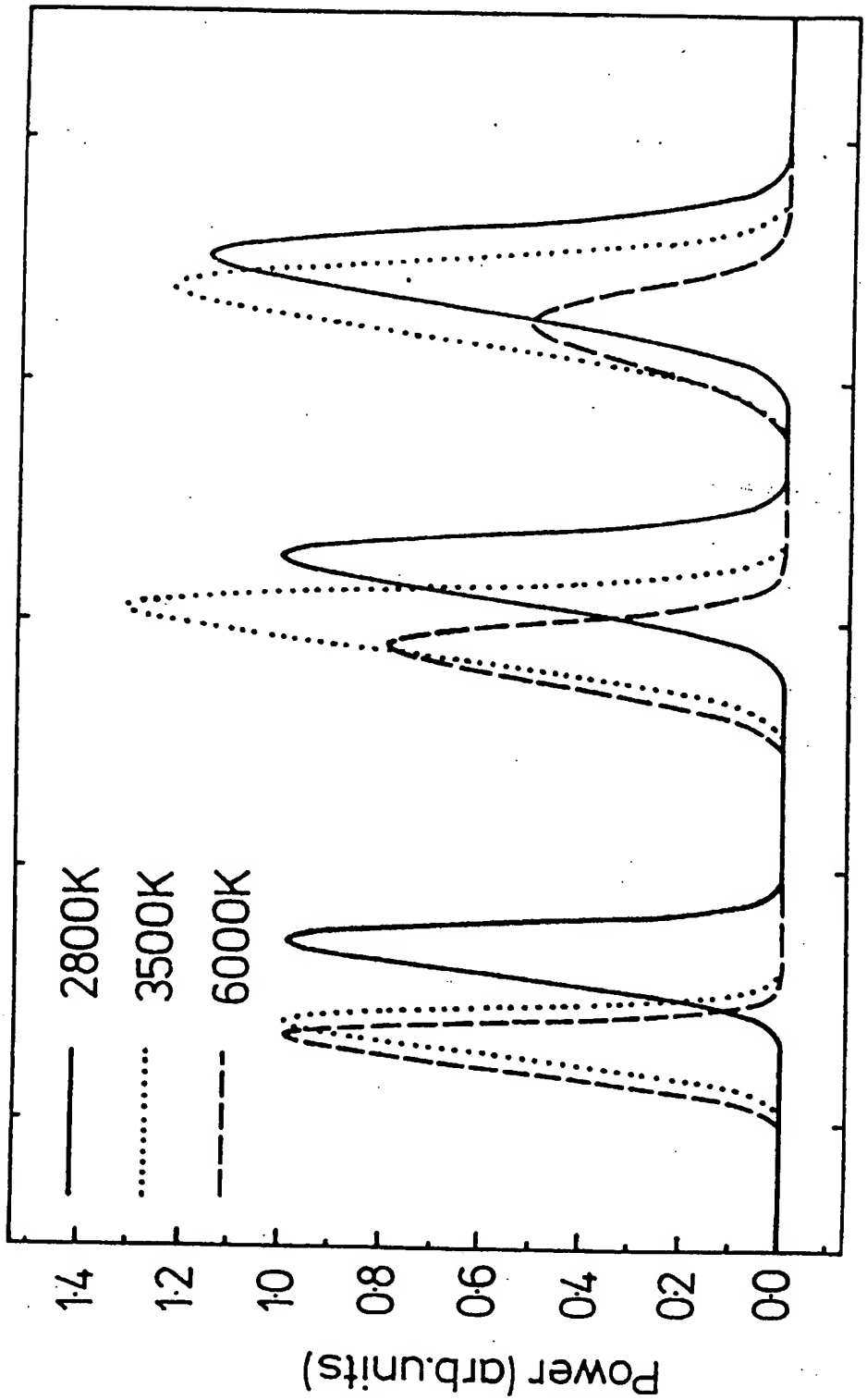

FIG.1

BEST AVAILABLE COPY

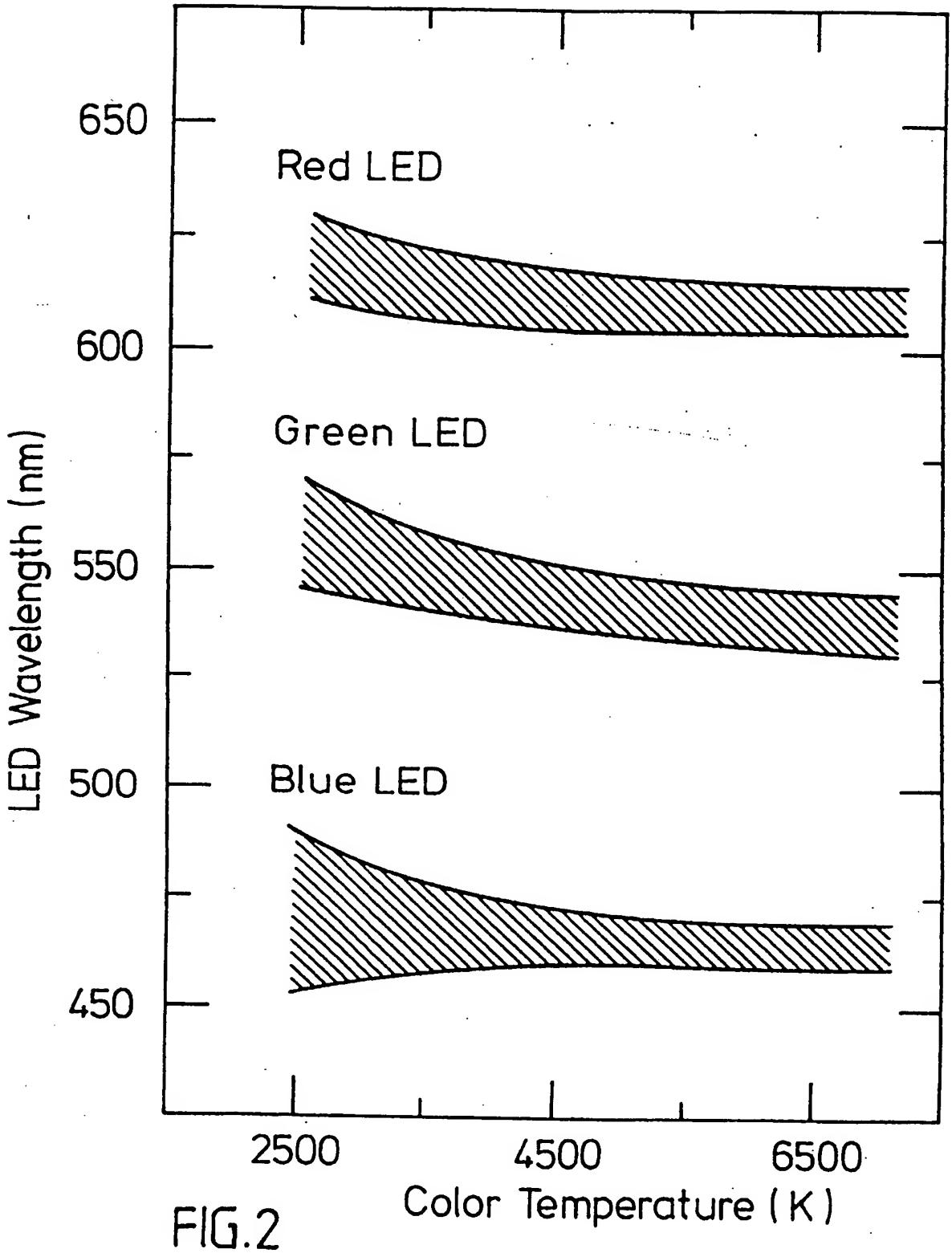

FIG.2

BEST AVAILABLE COPY

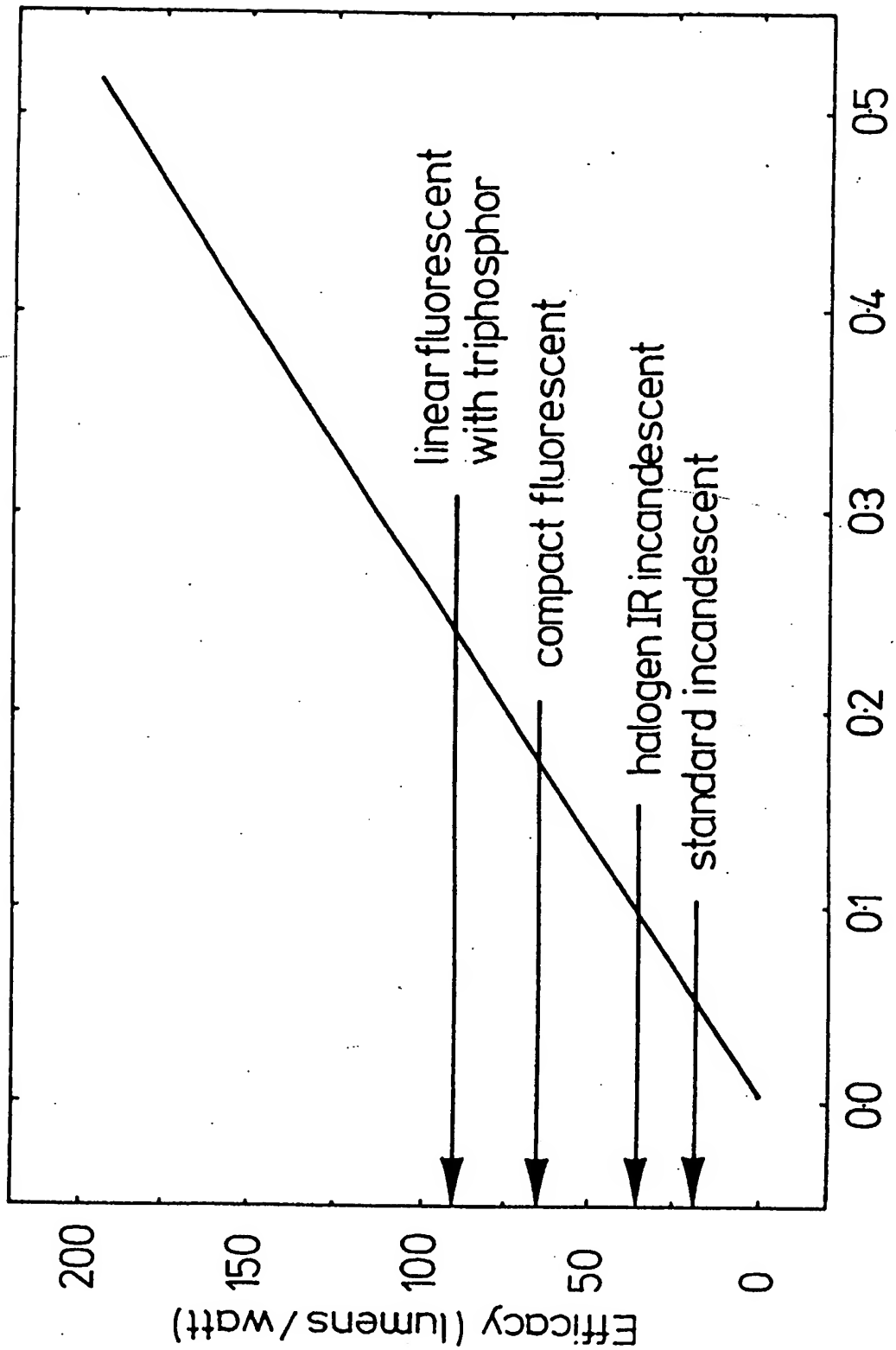

FIG.3

BEST AVAILABLE COPY

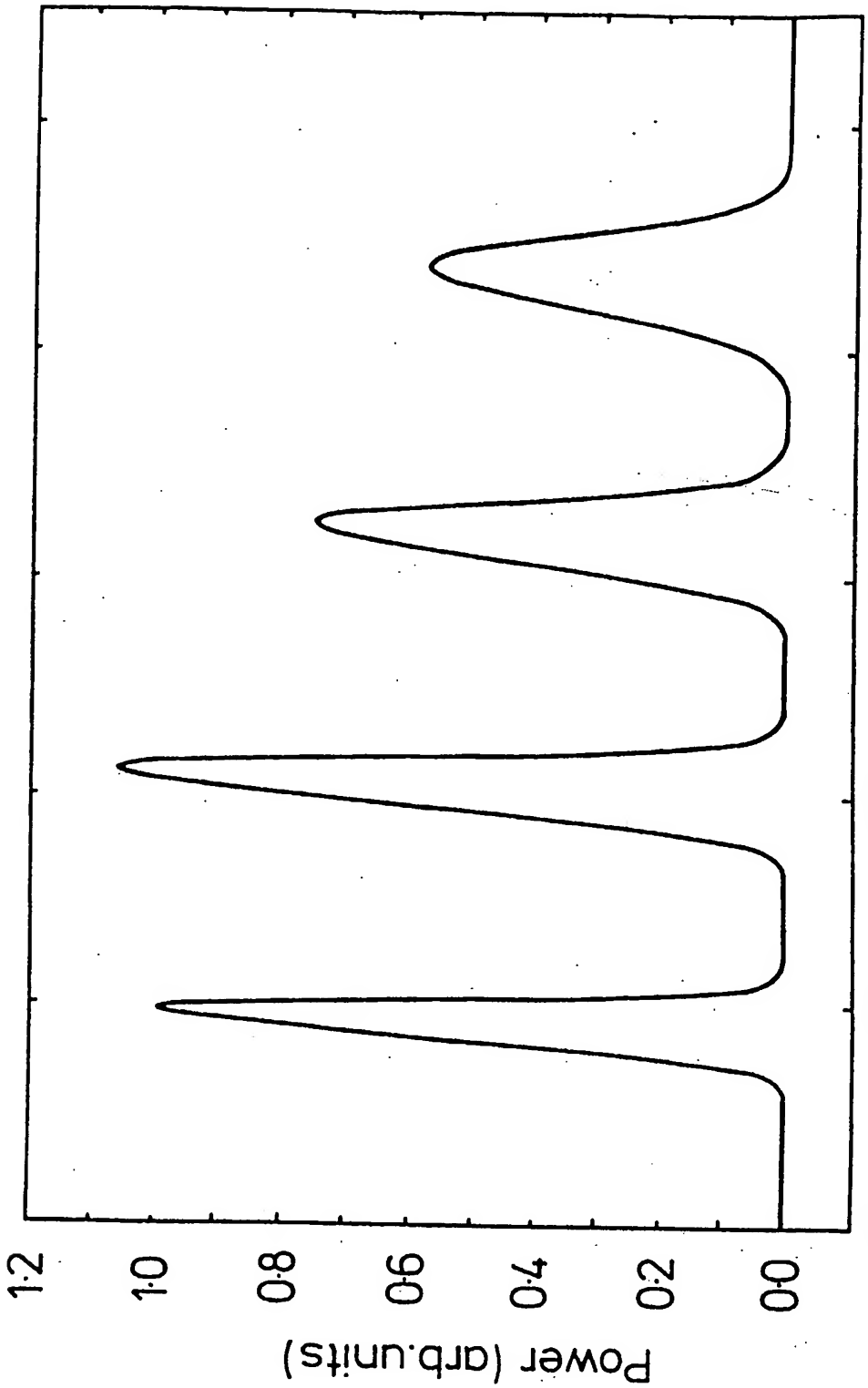

FIG.4

BEST AVAILABLE COPY